SERVICE BEHAVIOR OF ASPHALT CONCRETE

A TEN-YEAR STUDY

by

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A B S T R A C T

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Surface conditions were evaluated and samples of asphalt concrete and stone base were obtained twice yearly for a ten year period at 32 test points on eight heavily travelled highways in Oregon. A stepwise linear regression analysis was conducted to determine relationships that exist between different pavement properties and between pavement properties and service characteristics of the pavement.

Variables of time and condition that were considered in the project included years service, equivalent wheel loads, a pavement condition code, and wheel track depressions. Properties of the asphalt concrete included in the regression analysis were specific gravity, relative compaction, percent air voids, stabilometer S values on in-place and recompacted cores, cohesiometer values, penetration of recovered asphalt, asphalt content, and properties of aggregate gradation. Also included were properties of the granular base, ie., density, moisture content, relative compaction and gradation. Analysis of the asphalt concrete included samples of both base lift and top lift of pavement at locations in the wheel track and in the adjacent shoulder.

Although the stabilometer S values for the in-place material were typically low (usually 15 to 25) there was no evidence of pavement instability. The regression equations show that for these mixes the pavement service becomes worse as stabilometer values increase, indicating stability may be over emphasized at the cost of reduced flexibility. The study tends to confirm and to emphasize many accepted relations regarding pavement performance but also, some relationships are indicated by the equations that have not been widely recognized in the past. These indications may aid in the quest for more durable pavements.

Synopsis

The ten-year study of asphalt pavement behavior described herein was instigated to follow the changes that occur with time and traffic, and to supplement existing information on materials properties that contribute to more durable pavements. Measurement of surface characteristics and sampling of asphalt concrete and stone base was conducted twice yearly, during spring and fall seasons, at 32 test points. Properties of the asphalt concrete and stone base important to performance were measured in the laboratory for each sampling period. Samples were taken both in wheel track and shoulder areas to provide an indication of the effect of traffic.

Analysis of the various interrelationships between properties that affect service behavior utilized a stepwise linear regression program. The relative importance of the different properties to a given dependent property is indicated by the order in which the variables enter the regression equations. The correlation coefficients are generally low, but the equations provide a useful qualitative indication of the different relationships. A summary of the predominant indications provided by the equations is presented.

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INTRODUCTION

The design of asphalt concrete has developed from a rather uncertain art to a reasonably well-defined science during the last 20 to 30 years. Laboratory methods to evaluate design properties have become well established and reliable. Studies of material in-place have been less common. In an effort to refine the limits of the many properties known to influence the performance of asphalt concrete, the Oregon State Highway Division has conducted several long-term studies of asphalt concrete pavements (1). This paper presents findings from a ten-year study of the service behavior of pavements at 32 test points on eight different projects. Samples of asphalt concrete and base rock were obtained at intervals of approximately six months and subsequently analyzed for various characteristics of aggregate, asphalt, and mix. Along with the sampling, wheel track depressions were measured and the general pavement condition was observed. During the later years of the study, Benkleman beam deflections were obtained each spring season. The in-place density, moisture content and gradation were determined for the granular base each time of sampling.

Tests that were performed on the asphalt concrete throughout the project include the Hveem stability of the in-place material, stability after additional laboratory compaction, density, relative compaction, penetration of the recovered asphalt, percent air voids, thin film oven loss, asphalt content, and gradation of the aggregate in the mix. In addition to cores used to study in-place properties, larger samples were cut from the pavement to provide material for remolded briquets, asphalt properties and aggregate gradation.

The pavements studied on the project were designed on the basis of a predicted ten-year life although at the time of their design, traffic was categorized as very heavy, heavy, moderate, or light, without calculation of equivalent wheel loads as would be done at present. During the study, normal maintenance practices were continued without regard to the test points. Most of the sections were sealed during the study and some of the test point areas were patched. Materials added to the surface in the form of seals or patches were removed from the samples prior to laboratory analysis so that testing was done on the original pavement only. There would, of course, be some effect from the protection against weathering provided by the surface treatments.

PURPOSE

The project was initiated to evaluate the service performance of several asphalt concrete pavements and to distinguish the changes that occur with age and traffic. The principal physical characteristics were evaluated at the time of construction to provide a base for measurement of progressive changes. The projects on which the test points were located were selected to provide a geographical distribution representing the different climatic characteristics prevalent in the state, but each point utilized the design established for the section. No variations were made in the design or construction to create intentional variations in the performance. The purpose was to measure any changes that occurred in pavements designed and constructed according to the practices in effect at that time.

SCOPE OF PROJECT

Selection of the test point locations was based on the desire to cover the different climatic conditions in the state with studies on highways subjected to heavy traffic. Obviously, the choice was limited to the areas in which construction was in progress during the period the program was getting underway. Eight projects were selected. Three of these were in the western valley areas having a climate that is mild and relatively wet, having rainfall of about 40 inches per year. To represent the more severe climate, three projects were chosen in eastern Oregon in an area having more snowfall and hard freezing. Two projects in the southern portion of the state represent areas that have relatively high summer temperatures, lower precipitation (32 inches per year), and only slight wintertime freezing. No construction of heavy traffic highways was in progress in the arid portions of the state at the time.

Four test points were selected on each of the eight projects included in the study. Usually two points in the outer lanes and two points in the median lanes of four-lane freeway sections were used. One two-lane highway was chosen primarily because of the heavy log truck traffic it carried. Identification of the projects and design information on number of lanes, pavement structure thicknesses and subgrade soil classifications are provided in Table 1. The three projects having test points 1 to 12 are in eastern Oregon, the two projects having test points 13 to 20 are in southern Oregon, and the three projects having points 21 to 32 are in the western valley areas.

TABLE 1

PAVEMENT STRUCTURE AND SUBGRADE DETAILS

Highway Section	Test Point Nos.	No. Lanes	Asphalt Concrete Thickness	Cushion Course Thickness 3/4"-0 m'tl.	Base Course Size	Base Course Thickness	Subgrade Classification
Emigrant Hill-Deadmans Pass	1 to 4	4	4"	1 1/2"	1 1/2"-0	10"	A-1-b(0)
Meacham-Glover Sta. 140	5 to 8	4	4"	1 1/2"	2"-0	9 1/2"	A-2-7(0)
Meacham-Glover Sta. 369	9 to 12	4	4"	1 1/2"	2"-0	9 1/2"	A-2-7(0)
Jumpoff Joe Creek-Louse Creek	13 to 16	4	4"	1 1/2"	2"-0	9 1/2"	A-1-b(0)
Myrtle Creek-Fords Bridge	17 to 20	4	4"	2"	1 1/2"-0	6"	A-1-a(0)
Salem Bypass	21 to 24	4	4"	2"	2"-0	18"	A-4(8)
Valley Junction-Wallace Bridge	25 to 28	2	3 1/2"	2"	1 1/2"-0	16"	A-6(12)
Lebanon Road-Halsey Intchge.	29 to 32	4	4"	2"	2"-0	20 1/2"	A-7-6(18)

The procedure involved obtaining samples in the wheel track nearest the pavement edge and in the shoulder area away from concentrated traffic. The two samples were taken in each case at the same longitudinal position along the road, thus permitting comparisons of properties of pavements under the kneading action of traffic as opposed to the identical pavements having very little traffic. Care was taken to remove both the shoulder sample and the wheel track sample from the same lay-down panel.

Sampling and testing involved determination of properties of the base and top lifts of asphalt concrete and of the granular base rock. Also, wheel track depressions were measured and during the later portion of the study Benkleman beam deflections were obtained once a year.

Tests on the granular base included density, moisture content, relative compaction, grain size analysis, liquid limit and plastic limit. An air degradation test was not included originally, but was added about midway in the study.

The asphalt concrete studies included not only the properties of the in-place material, but of samples having additional laboratory compaction and of specimens remolded in the laboratory. The core analyses included in-place density, air voids, stabilometer S value, and cohesiometer value. In an effort to detect any changes in compactability due to changes in particle orientation or aggregate degradation caused by the traffic, the cores were reheated to 240°F in molds and recompacted by applying 160 blows at 450 psi with the kneading compactor. The density and stability determinations were repeated for each core after the recompaction and this density was used for calculation of relative compaction.

Along with the cores, larger samples were cut with an impact chisel to provide material for aggregate gradation analysis, asphalt content, and penetration of recovered asphalt. Asphalt recovered by the Abson method was tested for penetration at 77°F and 39.2°F and the thin film loss and penetration after thin film loss were determined. A portion of the cut sample was reheated and used to fabricate additional stabilometer specimens using the standard kneading compaction process adopted for all sample preparation in Oregon. Briquets were tested for stability, density, and cohesion and, after being reheated and subjected to a second compaction, the same properties were measured again. These tests were conducted for comparison with the in-place properties as well as for any discernible changes in compactability, stability or cohesion that accompany aging and traffic. Since the changes that occur in pavement components during service would be somewhat affected by the general characteristics at time of placement, the initial properties of the asphalt concrete are shown in Table 2 and the initial properties of the stone base are shown in Table 3.

Failure of asphalt pavements can be broadly categorized as rutting or shoving in mixes lacking stability, poor surface texture resulting from too little or too much asphalt, and cracking resulting from embrittlement or excessive flexing. Factors that contribute favorably to high flexibility and fatigue resistance generally reduce the stability. As all designers know, an asphalt concrete mix design involves compromise. One of the concerns that led to this long-term study was that stability might be over-emphasized at the expense of flexibility. The various stabilometer measurements were made to provide information on in-place values and corresponding values for the same material subjected to different laboratory compactions. Observations

TABLE 2

APPROXIMATE ASPHALT CONCRETE PROPERTIES

Test Points	1-4	5-8	9-12	13-16	17-20	21-24	25-28	29-32
Asphalt Content, %	5.3	4.9	5.9	5.4	5.2	4.7	4.8	5.4
Penetration Grade	85-100	85-100	85-100	85.100	85-100	85-100	85-100	60-70
Spec. Grav. of Mix	2.28	2.18	2.18	2.19	2.27	2.21	2.30	2.24
% Air Voids	11.4	13.5	13.1	8.9	9.1	11.4	13.2	11.1
S Value in Place	22	22	23	22	23	25	20	22
S Value, recompacted	43	53	52	45	51	54	59	49
Cohesion	293	190	216	286	250	275	316	239
3/4"-1/4", %	34.1	42.2	36.9	39.9	41.7	42.2	37.5	39.0
1/4"-#10, %	30.3	26.8	29.3	27.5	24.2	26.6	30.1	27.9
Ratio 1/4-10 / 1/4-0	0.51	0.51	0.51	0.50	0.45	0.50	0.52	0.50
P 200, %	6.8	3.4	3.6	3.7	3.5	5.0	6.1	3.8

TABLE 3

INITIAL PROPERTIES OF STONE BASE

Test Points	1-4	5-8	9-12	13-16	17-20	21-24	25-28	29-32
Dry Density, pcf	141	129	122	136	141	130	142	126
Relative Compaction, %	93.6	93.6	89.7	98.3	97.1	92.1	94.2	90.5
Moisture Content, %	5.6	6.6	7.9	5.9	5.2	4.4	4.8	6.6
Nominal Size	1 1/2"-0	2"-0	2"-0	2"-0	1 1/2"-0	2"-0	1 1/2"-0	2"-0
1 1/2"-3/4", %	17.2				13.8		22.9	
2"-1", %		14.5	17.1	19.5		17.1		22.1
Passing 1/4", %	41.8	43.3	38.9	42.7	52.3	32.8	41.0	32.5
Passing #200, %	7.9	4.5	4.7	5.5	7.8	4.0	8.9	5.4
Liquid Limit	22	26	35	25	21	18	22	30
Plasticity Index	1	1	9	2	2	0	2	9

made at the time of sampling concerning cracking, patches, seal coats, and other evidence of distress or maintenance were used to establish a pavement condition code ranging from zero to four as follows:

0 - No cracks, no seal, and no patches

1 - Sealed only, no patches

2 - Minor cracking or patching

3 - Major cracking or patching

4 - Multiple patching or severe cracking

The code is arbitrary and imprecise, but a numerical rating was desired for the analysis and no system of rating had been used during the study.

The other tests on the mixtures and components thereof were conducted with the hope that correlations would appear between given characteristics and properties associated with good service of long duration.

PROCEDURE

Since the various tests require removal of a significant area of pavement, each new sampling period required a different position to obtain undisturbed samples. The samples were taken four feet from the preceding location upstream to traffic flow so that any roughness from patches placed in previously sampled areas had no effect on subsequent tests.

When Benkelman beam measurements were made, they were the first activity of the testing procedure. Five readings were taken at 50-foot intervals in the wheel path and averaged, except that inconsistent readings were deleted. The wheel track depressions were measured at the sample site using the deviation from a 5.5-foot straightedge. After these measurements, samples of the pavement approximately 16 inches square were cut without water from the wheel track with an electrically-operated impact chisel. Density of the stone base was determined by using a sand of known loose density to measure the hole volume. Samples were obtained for granulometric analysis, air degradation, moisture content, liquid limit and plastic limit. The cut sample provided material for remolded specimens, asphalt content, gradation analysis, and properties of the recovered asphalt.

Two 4-inch diameter cores were then removed from the wheel track in line with the position of the cut sample for analysis of the base lift and top lift of asphalt concrete.

On the shoulder area beside the wheel track sample site, two 4-inch cores and two 6-inch cores were removed. The smaller cores were used for in-place properties of the top and base lifts and the 6-inch cores for properties of the recovered asphalt in the two lifts.

For laboratory testing of the mix, any material foreign to the original asphalt concrete such as a tack coat at the bottom or seals and patches at the top were removed from the sample by sawing. To get a sample height close to the desirable 2.5 inches, some base lift cores contained a small portion of top lift and, conversely, some tip lift samples included a portion of the base lift. Tests for aggregate gradation and asphalt content used material from each lift separately after removal of foreign material and cut aggregate particles.

Sampling was done semiannually, in the spring and in the fall, and testing was accomplished as time permitted along with the regular design and construction control testing by laboratory personnel. The sampling periods were selected to provide wet season and dry season values. It was expected that seasonal variations would appear in some properties; however, the scatter in test results masked any seasonal effect that might exist. The detailed analysis was not divided by season.

ANALYSIS

Although some periodic examination was made of the progressive changes in several of the factors under study, analysis during the study was very limited. A preliminary report (2) was prepared when the test points had been in service for periods ranging from 7.5 to 9.5 years. The report presented trends in changes of density of the base rock, specific gravity of asphalt concrete, air voids in asphalt concrete, and hardening of the recovered asphalt, all with respect to length of service. No analysis of the interactions between properties was attempted at that time.

At the conclusion of the ten-year period of sampling and testing, the values were tabulated for each property for each six-month interval of time. Each property was assigned an arbitrary code number for use in handling the many variables in a computer analysis of correlations and regression analyses. The properties and respective code numbers are listed in Table 4. Of these variables, numbers 85 and 86, the stabilometer S values of the remolded mix after a second compaction for the base and top lifts respectively were not tabulated for the analysis because it appeared the values obtained from laboratory compacted cores were generally similar in magnitude, but with perhaps a little less scatter. Tabulated values for the remaining properties were punched on cards to provide good flexibility in computer analysis with respect to handling the points individually or in various combinations. The code 99 values, cumulative 5000 lb. equivalent wheel loads, were estimated by using traffic volumes recorded at locations near the test points, classification counts from the nearest permanent recorder station, and factors to convert truck counts by axle classification to 5000 lb. EWL. Information on the division of truck traffic between the outer and median lanes was not obtained during the study and review of available literature provided little basis for an estimate. Ten percent of the outer lane EWL was used as an approximation for truck loads on the median lanes.

A stepwise regression analysis program, referred to as "Biomed 2" or BMD02R, (3) available through the Data Processing Unit of the Highway Division, was utilized for the project. In addition to the regression equations, this program provides a simple correlation matrix comparing each variable with each other variable which, for this project, generated a 48 by 48 matrix for the data tabulated. Although many of these comparisons have absolutely no meaning, the data processing specialists considered it easier to include all of the data rather than sort out those for which some correlation might be conceivable. In the determination of coefficients for linear multiple regression equations, the variables to be included for consideration were limited to those items thought to have some logical chance of influencing the dependent variable. Primarily, the purpose was to exclude the irrelevant factors between shoulder and travelled lane and between granular base, base lift and top lift of pavement. Equations were

TABLE 4

PROPERTIES INCLUDED IN STUDY

Code No.	Property
year	Length of time in service, years
51	Field density of stone base, lb. per cu.ft.
52	Relative compaction of stone base %
53	Moisture content of stone base %
54	Stone base passing 1/4 in. sieve, %
55	Stone base passing No. 200 sieve, %
56	Wheel track depressions, inch
57	Specific gravity of asphalt concrete, in lane, base lift
58	Specific gravity of asphalt concrete, in lane, top lift
59	Specific gravity of asphalt concrete, shoulder, base lift
60	Specific gravity of asphalt concrete, shoulder, top lift
61	Air voids in asphalt concrete, %, in lane, base lift
62	Air voids in asphalt concrete, %, in lane, top lift
63	Air voids in asphalt concrete, %, shoulder, base lift
64	Air voids in asphalt concrete, %, shoulder, top lift
65	Stabilometer S value in place, in lane, base lift
66	Stabilometer S value in place, in lane, top lift
67	Stabilometer S value in place, shoulder, base lift
68	Stabilometer S value in place, shoulder, top lift
69	Relative compaction of asphalt concrete, in lane, base lift
70	Relative compaction of asphalt concrete, in lane, top lift
71	Relative compaction of asphalt concrete, shoulder, base lift
72	Relative compaction of asphalt concrete, shoulder, top lift
73	Stabilometer S value recompacted, in lane, base lift
74	Stabilometer S value recompacted, in lane, top lift
75	Stabilometer S value recompacted, shoulder, base lift
76	Stabilometer S value recompacted, shoulder, top lift
77	Cohesion value in place, in lane, base lift
78	Cohesion value in place, in lane, top lift
79	Cohesion value in place, shoulder, base lift
80	Cohesion value in place, shoulder, top lift
81	Penetration of recovered asphalt 77F, in lane, base lift
82	Penetration of recovered asphalt 77F, in lane, top lift
83	Penetration of recovered asphalt 77F, shoulder, base lift
84	Penetration of recovered asphalt 77F, shoulder, top lift
85	S value of remolded mix, 2nd compaction, base lift
86	S value of remolded mix, 2nd compaction, top lift
87	Asphalt content, % by wt. of mix, base lift
88	Asphalt content, % by wt. of mix, top lift
89	Benkleman beam deflections, 15 kip axle, inch
90	Pavement condition code
91	Mix aggregate retained on 1/4 inch sieve, %, base lift
92	Ratio of 1/4 - 10 to 1/4 - 0 mix aggregate, base lift
93	Mix aggregate retained on 1/4 inch sieve, %, top lift
94	Ratio of 1/4 - 10 to 1/4 - 0 mix aggregate, top lift
95	Mix aggregate passing 1/4 and retained #10, %, base lift
96	Mix aggregate passing 1/4 and retained #10, %, top lift
97	Mix aggregate passing 200 sieve, %, base lift
98	Mix aggregate passing 200 sieve, %, top lift
99	Cumulative 5000 lb. equivalent wheel loads, millions

generated for 38 different variables of the 49 coded items in Table 4. The remaining variables are properties expected to influence other factors but not be influenced by the other factors.

To get some idea of what the computer could make of the maze of data, two points; Point 1 in eastern Oregon and Point 21 in the Willamette Valley, were run separately. Results from these two points were compared to find similarities and differences in the variables included in the equations. For these first runs, the F level for inclusion was set at 4.0, a value requiring a high degree of significance for inclusion in the equations. The F level, sometimes called a variance ratio, provides a measure of the level of confidence that there is a valid correlation between variables. The numerical value is related to the confidence limit depending upon the degrees of freedom of the variables. Seven of the equations included the same variables for Point 1 as for Point 21. Two more agreed there was no worthwhile correlation available and, of the rest, twelve included many of the same factors for both points with one point including additional or some different variables. Thirteen other equations were developed where entirely different variables were included for one point than for the other. This leaves five variables for which an equation was provided for one point, but not the other. This comparison led to the conclusion that an F level of 4.0 was too high for this type of study where sampling and testing errors are added to the actual variation in properties. Also, it was concluded the data would have to be considered in large blocks to provide manageable results. Point 21 was rerun after changing the F level for inclusion to 1.0, a value requiring little correlation for a variable to enter the regression equations. With this value and a programmed maximum of eight steps for each regression, equations were obtained for each of the 38 dependent variables. The coefficients of correlation ranged from above 0.99 in explaining the wheel track depressions and the pavement condition code down to 0.35 in explaining the variation in the material passing the No. 200 seive in the top lift of asphalt concrete. These values were encouraging since one would hope to explain such things as wheel track depressions, whereas the passing No. 200 material should not change, except possibly for a degrading aggregate. Between the extremes were 22 equations with correlation coefficients (multiple R values) above 0.85, nine equations with values between 0.70 and 0.85, and seven equations below 0.70. For the type of data involved in the study, the F limit of 1.0 for inclusion seemed satisfactory and was adopted for subsequent calculations.

Following this preliminary inspection, a program was introduced to combine the data to provide equations for the average of the 32 test points and also averages for regional groups of eastern Oregon, southern Oregon, and western valley points. The Lebanon Road-Halsey Interchange project, having test points 29 to 32, used 60 - 70 penetration asphalt cement, while all other projects used 85 - 100 penetration material. For this reason, points 29 to 32 were averaged separately from the other valley points. The printouts for these regional groups were inspected for similarities in the variables included in the regression equations for several of the more significant properties. Although many of the same variables appear quite consistently, there are many differences in the variables found significant in the regressions. Also, a given variable may have a positive sign for one group of test points and a negative sign for another group which leads one to conclude the correlation is a coincidence and not really of any importance. The averaging of test point data was done to smooth some of the variations due to testing, but it is recognized that averaging may not be appropriate for some properties. The study attempts to detect rather small influences of time or other properties, and the sampling and testing scatter at an individual test point is often great enough to obscure a relationship that may appear when groups of data are averaged. It was expected that characteristic trends would appear between groups of averaged data.

The averaging of test point data did tend to bring out a higher degree of consistency as to which variables were brought into the equations and the order of importance of those variables to the correlation. Generally, the first two or three properties brought into equations for a given dependent variable were consistent. Less important properties often varied from one equation to another and sometimes the sign for a given property changed from positive to negative between equations indicating the correlations were coincidental.

Although the averaging of data started to emphasize some important relationships, others went undetected in the averaged data. For example, the effect of low air voids versus high air voids on the loss in penetration of the asphalt does not show up in using averages. In order to bring out the importance of this and similar relationships, it was necessary to view the properties individually, but to combine them into more general regression equations. This was done by processing the concatenated data for all 32 test points together, and also for the regional groups of eastern, southern, and valley points. The equations determined in this analysis had lower multiple correlation coefficients, but the importance of the interrelationships between mix properties did appear with some consistency.

Properties of Stone Base

The density of the stone base shows an increase during the study for all of the projects. The equations for the different regional groups of points and for the 32 points combined selected years service as the most significant correlation. Although the change in density should be traffic related, the cumulative wheel loads were found less significant than time. Correlation coefficients for density were low so most of the variation remains unexplained. The trends indicated by the equations for all points combined show an increase in density with years service, an increase with higher percentages passing No. 200, a decrease with higher percentages passing 1/4 inch, and an increase with increased EWL, with importance to the correlations being in the order listed. Only years service and percent passing No. 200 show up in the equations for regional groups of test points.

The relative compaction of the stone base has a higher correlation coefficient since properties such as particle shape, texture, and specific gravity are removed as variables. For the overall 32 points combined, the equation for relative compaction has an inverse relationship to moisture content as the most important variable followed by direct relationships of years service, percent passing No. 200, equivalent wheel loads, and percent passing 1/4 inch.

The other properties of the stone base included in this research, i.e., moisture content, passing 1/4 inch and passing No. 200, had little correlation with the variables of years service and cumulative wheel loads. The equations do confirm that there was no measureable degradation. All aggregates met the requirements of the Oregon Air-degradation test; however, the two projects having test points 25 to 28 and 29 to 32 used aggregates not far above the rejection limit.

Properties of Asphalt Concrete

The various properties of the asphalt concrete will be discussed first in terms of general trends, followed by more specific comments on the regression equations.

The specific gravity of the asphalt concrete generally relates first to the air void content followed by the percent passing No. 200, decreasing with higher air voids and increasing with higher passing No. 200. In some cases, the passing No. 200 enters first with air voids second, but these are consistently the first two variables in the equations for the concatenated data. The third variable is usually the relative compaction and this is followed by other gradation variables, but beyond the third term there is little consistency. Some equations pick the percent retained on the 1/4 inch sieve next, showing increased density with an increase in percent retained. Other equations find the ratio of 1/4" - #10 to 1/4" - 0 being next in importance; again with a positive relationship. Some equations include percent asphalt, equivalent wheel loads, years service and other variables, but these items contribute little to the correlation.

The percent air voids equations are generally most influenced by the relative compaction followed frequently by the stabilometer "S" values of the recompacted mix. Air voids increase with reduced relative compaction and with an increase in S values. Frequently high in the order of influence is the ratio of 1/4" - #10 to 1/4" - 0, air voids increasing with higher ratios. Effects of years service and cumulative wheel loads enter some of the air voids equations in the third to eighth terms, but it is apparent that these mixes were little affected by time or traffic. The equivalent wheel load term does consistently enter the equations for the top lift before it enters the base lift equations. This indicates some slight densification of the top lift does occur under traffic.

The stabilometer S value of the in-place material has the strongest correlation with relative compaction, higher S values being associated with higher relative compaction. There is also a strong positive effect in the travelled lanes from the equivalent wheel loads. Entering the equations with less regularity are cohesion, percent passing No. 200, air voids content, and years service. Although not a strong influence, the in-place S value consistently has a negative relationship with years service, an unexpected characteristic.

After the in-place stabilometer values were determined, the cores were heated and recompacted to provide a basis for evaluation of relative compaction. The regression equations for relative compaction usually relate first to the in-place S value and second to the percent air voids, increasing with higher S values and decreasing with higher air voids. Next-most frequent is a negative relationship to the percent passing the No. 200 sieve. Less consistent, but common, are entries of percent asphalt having negative coefficients, ratio of 1/4" - #10 to 1/4" - 0 with positive coefficients, and the percent passing 1/4" and retained on #10 having negative coefficients. Scattered entries of coehesion, penetration, and S values of the recompacted samples were found. Also, years service and cumulative wheel loads frequently appear as a positive, but not very significant, influence.

Stabilometer S values of the recompacted samples related first to percent asphalt for the top lift, but this variable never entered the equations for the bottom lift. Apparently some top lift samples were close to the critical asphalt content and lost stability upon recompaction while this did not occur in the bottom lift samples. Other items important in the equations are air voids content, in-place S values, cohesion, and ratio of 1/4" - #10 to 1/4" -0. As with the in-place S values, the coefficients for cumulative wheel loads have positive values while those for years service have negative values. Neither loads nor service contribute much to the correlations, but it is interesting that the signs are consistently opposite.

Cohesiometer values increase with years service as the most important variable followed generally by the percent passing No. 200, again a positive relationship. Following as important variables are commonly the in-place S values and the percent air voids, S values having positive coefficients and air voids negative. The equations for the concatenated data for all 32 test points have both percent asphalt and penetration of recovered asphalt with negative coefficients while these variables enter into equations for several regional groups with positive coefficients. In neither case do the variables contribute appreciably to the correlations.

Without exception, the equations for penetration of the recovered asphalt show an inverse relationship with years service as being most important. The next two factors are percent air voids with a negative coefficient and percent asphalt with a positive coefficient. Items that appear irregularly are relative compaction, passing No. 200, and cumulative wheel loads. The hardening of the asphalt as measured by loss in penetration occurs rapidly as first and at a progressively declining rate with longer service. This type of variation can be expressed quite accurately by a hyperbolic equation of the form:

$$\text{Penetration loss} = \frac{\text{Years service}}{a+b\ (\text{years service})}$$

where the coefficients a and b vary from point to point, being influenced by properties of the mix such as percent asphalt, air voids, relative compaction, asphalt characteristics, and aggregate gradation. Although the linear regression equations have a less precise fit for a given point, the regression equations do bring in the other important variables. Nonlinear functions can sometimes be handled in linear regressions, however, this was not attempted in this study. When inspected against years service, the loss in penetration had a greater nonlinearity than the other variables; but several properties have a nonlinear trend, notably the increase in density of the stone base which occurred rapidly during the early years and almost stabilized after about five years.

None of the various aggregate properties of the mix were considered to be dependent variables except for the possibility of degradation with time and traffic. Inspection of the data did not indicate any change in gradation, so only the percentages passing No. 200 in base and top lifts were included in the computer analysis. The resulting equations confirmed there was no significant degradation. When included, years of service generally had a negative coefficient and equivalent wheel loads a positive coefficient, but neither was significant.

Performance Properties

Several factors involve the performance of the total pavement structure, asphalt concrete and granular base combined. These are the wheel track depressions, Benkleman beam deflections and the pavement condition code. All variables thought to have any conceivable effect on these items were included in the analysis. Included were 26 items for wheel track depressions and 28 items each for Benkleman beam deflections and pavement condition code.

The equation for wheel track depressions, resulting from the data for all 32 test points, included the following variables, listed in the order of their importance to the correlation: equivalent wheel loads, cohesiometer value for base lift, in-place S value of base lift, percent air voids in base lift, percent relative compaction of top lift, percent passing No. 200 in top lift, percent asphalt in top lift, and the percent passing 1/4 and retained on No. 10 in top lift. Except for the last two variables, the coefficients have positive signs. Several of these signs are opposite to what might be expected if the given variable is viewed alone, but considering the complex interaction between properties as affected by time and traffic, they seem reasonable. The major influence on wheel track depressions is the cumulative wheel loads, as would be expected. Beyond this, the items included in equations for regional groups of points differ some from those found most important to the correlation for the overall data. This is not surprising since the wheel track depressions vary appreciably between groups. Maximum depressions in eastern Oregon were 5/16 inch, occurring primarily from additional compaction of the mix. Several points in the western valley areas had depressions slightly over one inch after 10 years service. For this much depression, some movement of the mix must have occurred, but the regression equation includes only equivalent wheel loads, air voids content of base and top lifts, passing No. 200 in top lift, ratio of 1/4" - #10 to 1/4" - 0 in top lift, and years service. Stability and relative compaction factors did not enter the equation, nor did any factors related to the granular base.

While the regression equations for wheel track depressions were influenced mainly by loads and mix properties, the Benkelman beam deflections relate heavily to properties of the stone base. The variables selected in the Benkelman beam regression for the concatenated data for all 32 test points, with the sign of the coefficient in parentheses, are: wheel track depression (+), percent passing 1/4" in stone base (-), percent asphalt in top lift (-), percent passing No. 200 in stone base (+) ratio of 1/4" - #10 to 1/4" - 0 in top lift (+), percent air voids in base lift (-), cohesiometer value for base lift (+) and years service (-). Of 28 variables to choose from, these provided the best correlation. Again, some of the signs for Benkelman beam deflections are opposite to anticipated relationships, but it is difficult to visualize the various subtle effects that one variable has on the others.

The final regression equation for the project is for the pavement condition code. This code was established to express numerically the serviceability of the pavement in terms of the prevalence of cracking or patching that occurred during the study. To reiterate, the ratings go from zero for a pavement free of cracks that had received no maintenance to four for a pavement that was cracked severely or that had required patching several times at a given point. The regression equation for the overall data includes the following variables, listed in the order of importance to the correlation: years service, in-place S value of top lift, percent moisture content in stone base, wheel track depressions, percent air voids in base lift, equivalent wheel loads, ratio of 1/4" - #10 to 1/4" - 0, and penetration of the asphalt in the top lift. Each coefficient has a positive sign. The fact the equation relates first to years service instead of equivalent wheel loads is probably caused by the fact that thin patches were often placed over both the median and outer lanes for smoothness and uniformity even though only the outer lane may have needed maintenance at the time. Records were not detailed enough to permit adjustment of the pavement condition code for this type of case. The variables selected in the regression analysis were from among 28 possibilities and it is interesting to note those of major importance. The second item, in-place S value of top lift, is logical in that high values result from dry or brittle mixes as does pavement cracking. Third in the correlation is the moisture content of the stone base, high moisture leading to early distress. Also deserving comment is the fifth item, the percent air voids in the base lift. The high air voids content of these mixes would result in rapid embrittlement which, in turn, would lead to pavement cracking.

Multiple Regression Equations

Although the principal benefit of the regression equations in this study is to bring out the interrelationships between properties in a qualitative way, it may be useful to illustrate some of the actual coefficients. A tabulation of all of the equations from the analysis of the concatenated data from the 32 test points is provided in the Appendix. The equations are all of the form:

$$Y = A_o + A_1 X_1 + A_2 X_2 + A_3 X_3 + \dots A_n X_n$$

Where Y is the desired relationship,

A_o is a constant,

A_1 to A_n are coeffieicnts and

X_1 to X_n are dependent variables

measured in the study.

The number of variables included in the equations was controlled by an F level for inclusion of 1.0 with a maximum of 8 variables. The correlations resulting from the concatenated data from all 32 test points are generally none too precise. Deviations resulting from sampling and testing would be high and measures of the quality of construction are lacking. Also, climatic conditions and subgrade properties have no input into the equations. Correlations for individual projects and regional groups are higher, but the combined data serves better to bring out the variables having overall importance to pavement performance.

To illustrate the equations, the percent relative compaction of the top lift asphalt concrete in the travelled lanes can be estimated by:

$$\%RC = 100.29 - 0.277\ (\%\ \text{Air voids}) + 0.089\ (\text{In-place S value})$$
$$-0.0015\ (\text{In-place cohesion}) - 0.0177\ (\text{Pen at 77F})$$
$$- 0.446\ (\%\ \text{Asphalt} - 0.0796(\%\ \text{P1/4" \& R \#10})$$
$$+ 0.109\ (\%\text{P \#200}) + 0.0157\ (\text{EWL, millions})$$

The in-place stabilometer S value of the top lift asphalt concrete in the travelled lanes can be calculated by:

$$S = -88.89 + 0.222\ (\text{EWL, Millions}) + 1.029\ (\%\text{RC})$$
$$+0.0149\ (\text{Cohesion in place}) + 0.0943\ (\%\ \text{Ret. 1/4"})$$
$$+0.414\ (\%\ \text{Air voids}) +0.0497\ (\text{Pen at 77F})$$
$$-0.551\ (\%\text{P200}) - 0.295\ (\text{Years service})$$

Penetration of the recovered asphalt at 77F for the top lift pavement is approximately:

$$\text{Pen} = 99.63 - 3.244\ (\text{Years service}) + 4.088\ (\%\ \text{Asphalt})$$
$$+0.457\ (\%\text{P200}) - 0.463\ (\%\ \text{Air voids})$$
$$-0.793\ (\%\ \text{RC})$$

An approximation for the percent relative compaction of the stone base is:

$$\%RC = 92.454 - 1.542\ (\%\ \text{Moisture}) + 0.540\ (\text{Years service})$$
$$+0.825\ (\%\ \text{P200 in stone base}) + 0.107\ (\text{EWL, millions})$$
$$+0.088\ (\%\text{P1/4" in stone base})$$

The equation for Benkelman beam deflections is:

$$\text{BB defl,in.} = 0.0258 + 0.0087\ (\text{Wheel track depr.})$$
$$-0.00028\ (\%\text{P1/4" in stone base}) - 0.0022\ (\%\ \text{Aspahlt top lift})$$
$$+0.0006\ (\%\text{P200 in stone base}) +0.0240(\text{Ratio 1/4-10 to 1/4-0 top lift})$$
$$-0.0003\ (\%\ \text{Air voids base lift}) +0.00001\ (\text{Cohesion base lift})$$
$$-0.00036\ (\text{Years service})$$

The pavement condition code can be determined by:

Cond. Code = -5.359 + 0.196 (Years service) +0.062 (S value top lift)

+0.177 (% Moist. in stone base) +0.659 (Wh track depr.)

+0.075 (% Air voids base lift) +0.026 (EWL, millions)

+3.027 (Ratio 1/4-10 to 1/4-0 top lift) +0.0094 (Pen at 77F top lift)

Where values near zero indicate excellent service and values near four denote pavements requiring extensive maintenance.

The variables in these examples are arranged in descending order with regard to their importance to correlation.

The equations illustrate the type of output obtained for 38 different variables for which some interdependence seemed likely. As mentioned above, their principal value is in showing the general order of importance of the various properties against each other. Equations similar to those illustrated were obtained for the various asphalt mix properties for top lift and base lift at locations in travelled lane and shoulders. Thus, four equations were available for many given properties. Generally, the first two or three variables important to a correlation were fairly consistent between equations, but the less important items have no consistency. Since the regression coefficients are dependent on the particular variables included, the numerical values are appreciably different between equations. However, the solutions obtained from substitution of typical values into the several equations for a given property are similar.

Summary

The study was initiated to determine measurable changes in the various properties and characteristics of asphalt pavements under service conditions. Each project was designed and constructed in accordance with the procedures in effect at the time; no variations were introduced to create intentional differences in performance. Measurements made during the 10-year study were inspected first to identify changes occurring with time, but to determine the interdependence of individual properties on the overall service behavior, a multiple linear regression analysis was employed. This analysis confirmed, in a qualitative way, the known relationships between such properties as compaction, air voids, asphalt content, and penetration of the recovered asphalt, among others. In addition, some measure of the influence of time and traffic was obtained for many of the properties.

The following summary statements are based on indications provided by the regression equations. In many cases, the order of importance of independent variables on a given dependent variable is not unanimous, but the statements represent predominant indications.

1. Densities of the stone base show an increase for all projects with outer lanes having a greater increase than median lanes. Values during the final four years remained nearly constant, the early years showing most of the change. Time proved a better correlation than equivalent wheel loads although both caused increased density. Stone base densities also increase with greater percentages passing No. 200 and with smaller percentages passing 1/4 inch.

2. No degradation of the stone base occurred.

3. Density of the asphalt concrete is increased primarily by reducing air voids and by increasing the percent passing No. 200. The densities of mixes used on the test projects were increased only slightly by equivalent wheel loads and years service.

4. The percent air voids relate inversely to relative compaction and directly to the Hveem stabilometer S value of the recompacted mix as the two most common variables. As the ratio of 1/4" - #10 to 1/4" - 0 is increased, the mix becomes more "open" and the air voids content is increased. The cumulative equivalent wheel loads term indicates an average reduction in percent air voids of about 1 percent in the base lift and 2.5 percent in the top lift from 10 years of freeway traffic. Initial air voids contents were high, generally around 10 percent.

5. Stabilometer S values for in-place materials increase with higher relative compaction, with higher traffic volumes, with higher percentages passing No. 200, and with higher cohesion. Although the in-place S values were generally low, no pavement instability existed on the test projects. S values of the in-place material were predominately in the range of 15 to 25. Additional compaction of the cores in the laboratory increased the stability values to the range between 50 and 70 for most pavements. In a few instances, the additional compaction caused a reduction of stability on samples having high asphalt content.

6. Cohesiometer values increase with years service, with percent passing No. 200, and with in-place S values, in that order with regard to the correlation. Also, cohesion increases with a reduction in penetration of the recovered asphalt, as one would expect.

7. Penetration of the recovered asphalt has inverse relationships to years service and air voids content and a direct relationship to asphalt content as the three most important variables.

8. Wheel track depressions increase with equivalent wheel loads as the most important factor in the correlation. Following this

are various materials properties, several of which have signs opposite to expected values. The depressions correlate directly with cohesion of base lift, S value of base lift, air voids in base lift, and relative compaction of the top lift, in that order. No properties of the stone base enter into the regression equation.

9. The Benkelman beam deflections relate first to the wheel track depressions and this is followed by inverse correlations with percent passing 1/4 inch in stone base and percent asphalt in top lift and then by a positive relationship with percent passing No. 200 in stone base. It is interesting to note that these tests indicate Benkelman beam deflections are reduced by having more passing the 1/4 inch sieve and less passing the No. 200 in the stone base. While no properties of the stone base affected the wheel track depressions, the stone base has a major influence on the Benkelman deflections.

10. An arbitrary numerical pavement condition code was devised to enable a correlation with the other properties in the multiple regression analysis. The condition code was not a part of the semiannual inspection, but values were assigned from notations of cracking, seals, patching and overlays made in conjunction with the sampling. The regression equation for condition relates first to years service instead of equivalent wheel loads, probably because maintenance was extended over both the outer and median lanes to provide a smooth surface. Second in importance was the stabilometer S value for the top lift, higher S values corresponding to pavements having more cracking and needing more maintenance. Third was the moisture content in the stone base, higher moisture resulting in poorer service. These were followed by wheel track depressions, percent air in base lift, equivalent wheel loads, ratio of 1/4" - #10 to 1/4" - 0 in top lift, and penetration of the asphalt in the top

lift. In each case, higher values correspond to pavements needing more maintenance. The last item contributes very little to the correlation, but its effect is opposite to that expected. The correlation is probably coincidental. The other factors affect performance as would be expected, more maintenance being needed for more brittle mixes.

Implementation

In a long duration study of this type, implementation of findings takes place as the study progresses. Many changes in pavement structure and asphalt concrete mix design have been made since the ten-year study was initiated. A number of these changes were influenced by results and observations of the service behavior study. Included are the following:

1. To achieve optimum moisture for compaction of aggregate bases and to prevent segregation of the material during processing, all base materials are plant mixed to uniform moisture and then placed with a spreader.

2. Specifications were introduced to more closely control the gradation of aggregate bases by requiring that the ratio of 1/4" - #10 to 1/4" - 0 be between 40 and 60 percent. This provides a gradation giving high density without loss of strength from over-sanding.

3. The Oregon air-degradation test was developed during the study to identify troublesome aggregates. Values obtained during the ten-year study helped to fix permissible limits. Also, the study indicates no significant change in air degradation values occur in service.

4. Recognition that better control of stone base properties was important to good service led to adoption of the sand equivalent test for aggregates. Although not a part of the service behavior study, observations during the study contributed to an understanding of aggregate properties.

5. Specifications to require 95 percent relative compaction of aggregate bases were introduced during the study, again with some influence from observation of the test points. Previous specifications had been based on weight of roller and coverages.

6. Evidence that even though the in-place stabilometer S values were low, there was no problem with pavement stability has led to several changes in mix design. One of these was to increase the asphalt content to provide a more dense and more flexible pavement. The control of the ratio of 1/4" - #10 to 1/4" - 0 between 42.5 and 57.5 percent provides a relatively open gradation that permits thick asphalt films without flushing. More fatigue resistant pavements have resulted.

7. Emphasis in design has centered on control of air voids content and on the index of retained strength on immersion-compression specimens since it was established that stability is not a problem with normal gradation and crushing requirements.

8. The low densities and high air voids contents found so frequently in the ten-year study had an influence in putting greater emphasis on construction control. Compaction requirements were changed and a greater effort was placed on obtaining adequate compaction. Data from the test points demonstrated a very rapid loss in penetration of the recovered asphalt in mixes having high air voids and a much less

severe loss in mixes having lower air voids content. Mixes having the higher retained penetration exhibit better fatigue resistance, as one would expect.

9. The drying of aggregates for asphalt concrete received additional attention as a result of the eastern Oregon projects. Residual moisture in the aggregate caused the mix to have the appearance and consistency associated with excess asphalt while it actually had a low asphalt content. Although specifications limiting moisture to 0.5 percent existed, more careful testing for compliance resulted from observation of these projects.

The regression equations generally confirm relationships between variables known to exist, but occasionally unexpected correlations appeared. Also, the order of importance and the nature of the effect sometimes differed from that anticipated. Further study will be made of these equations to determine if other design changes are suggested by them. For instance, the ratio of 1/4 - #10 to 1/4" - 0 in the asphalt concrete enters many equations and in a majority of cases the effect of increasing the ratio is to worsen the dependent variable. This suggests that the limits for the ratio may be higher than optimum, a possibility that will be investigated. Other things of this nature that indicate improved performance may be obtained by modifying proportions or procedures will be investigated to continue the implementation of the research results.

Conclusions

This systematic evaluation of pavement performance has provided a measure of the interrelationships between variables over a long period of time. Frequently, this was merely confirmation of known factors, but the study did show the relative importance of various items on the ten-year service behavior. The study has had an influence on improvements in asphalt concrete design and construction control and as a result, better service is expected from pavements placed today.

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APPENDIX

The following tabulation provides linear regression equations for the concatenated data from the 32 test points. To conserve space, the variables are represented by their respective code numbers. The independent variables are listed in declining order with regard to the contribution they make to the correlation. Table 4 is repeated from the report for convenience in identifying the property represented by a given code number.

TABLE 4

PROPERTIES INCLUDED IN STUDY

Code No.	Property
year	Length of time in service, years
51	Field density of stone base, lb. per cu.ft.
52	Relative compaction of stone base %
53	Moisture content of stone base %
54	Stone base passing 1/4 in. sieve, %
55	Stone base passing No. 200 sieve, %
56	Wheel track depressions, inch
57	Specific gravity of asphalt concrete, in lane, base lift
58	Specific gravity of asphalt concrete, in lane, top lift
59	Specific gravity of asphalt concrete, shoulder, base lift
60	Specific gravity of asphalt concrete, shoulder, top lift
61	Air voids in asphalt concrete, %, in lane, base lift
62	Air voids in asphalt concrete, %, in lane, top lift
63	Air voids in asphalt concrete, %, shoulder, base lift
64	Air voids in asphalt concrete, %, shoulder, top lift
65	Stabilometer S value in place, in lane, base lift
66	Stabilometer S value in place, in lane, top lift
67	Stabilometer S value in place, shoulder, base lift
68	Stabilometer S value in place, shoulder, top lift
69	Relative compaction of asphalt concrete, in lane, base lift
70	Relative compaction of asphalt concrete, in lane, top lift
71	Relative compaction of asphalt concrete, shoulder, base lift
72	Relative compaction of asphalt concrete, shoulder, top lift
73	Stabilometer S value recompacted, in lane, base lift
74	Stabilometer S value recompacted, in lane, top lift
75	Stabilometer S value recompacted, shoulder, base lift
76	Stabilometer S value recompacted, shoulder, top lift
77	Cohesion value in place, in lane, base lift
78	Cohesion value in place, in lane, top lift
79	Cohesion value in place, shoulder, base lift
80	Cohesion value in place, shoulder, top lift
81	Penetration of recovered asphalt 77F, in lane, base lift
82	Penetration of recovered asphalt 77F, in lane, top lift
83	Penetration of recovered asphalt 77F, shoulder, base lift
84	Penetration of recovered asphalt 77F, shoulder, top lift
85	S value of remolded mix, 2nd compaction, base lift
86	S value of remolded mix, 2nd compaction, top lift
87	Asphalt content, % by wt. of mix, base lift
88	Asphalt content, % by wt. of mix, top lift
89	Benkleman beam deflections, 15 kip axle, inch
90	Pavement condition code
91	Mix aggregate retained on 1/4 inch sieve, %, base lift
92	Ratio of 1/4 - 10 to 1/4 - 0 mix aggregate, base lift
93	Mix aggregate retained on 1/4 inch sieve, %, top lift
94	Ratio of 1/4 - 10 to 1/4 - 0 mix aggregate, top lift
95	Mix aggregate passing 1/4 and retained #10, %, base lift
96	Mix aggregate passing 1/4 and retained #10, %, top lift
97	Mix aggregate passing 200 sieve, %, base lift
98	Mix aggregate passing 200 sieve, %, top lift
99	Cumulative 5000 lb. equivalent wheel loads, millions

REGRESSION EQUATIONS

Cd51 = 102.16 + 3.230 (year) + 3.551 (Cd55) - 0.416 (Cd54) + 0.224 (Cd99)

Cd52 = 92.45 - 1.542 (Cd53) + 0.540 (year) + 0.825 (Cd55) + 0.107 (Cd99) + 0.088 (Cd54)

Cd53 = 16.48 - 0.114 (Cd52) + 0.048 (Cd55)

Cd54 = -2.505 - 0.190 (Cd99) + 0.391 (Cd52) + 1.179 (Cd53) - 0.216 (year)

Cd55 = -5.453 + 0.122 (Cd52) - 0.0604 (year) - 0.0142 (Cd99) + 0.0704 (Cd53)

Cd56 = -0.940 + 0.0181 (Cd99) + 0.00017 (Cd77) + 0.00409 (Cd65) + 0.0126 (Cd61) + 0.0113 (Cd70) + 0.0262 (Cd98) - 0.0422 (Cd88) - 0.00082 (Cd96)

Cd57 = 1.331 - 0.016 (Cd61) + 0.0271 (Cd97) + 0.00686 (Cd69) + 0.00417 (Cd91) + 0.0048 (Cd95) + 0.00108 (Cd99) + 0.00037 (Cd81) + 0.00107 (year)

Cd58 = 1.451 - 0.0015 (Cd62) + 0.0231 (Cd98) + 0.0109 (Cd70) - 0.0253 (Cd88) - 0.4976 (Cd94) + 0.00484 (Cd96) + 0.00138 (Cd99) + 0.00056 (Cd82)

Cd59 = 0.943 - 0.0195 (Cd63) + 0.0279 (Cd97) + 0.01196 (Cd71) + 0.00338 (Cd91) + 0.00467 (Cd95) + 0.00118 (year)

Cd60 = 2.565 + 0.0313 (Cd98) - 0.0189 (Cd64) + 0.00233 (Cd84) - 0.0464 (Cd88) - 0.2193 (Cd94)

Cd61 = 69.853 - 0.6913 (Cd69) + 0.0848 (Cd73) + 18.382 (Cd92) - 0.0579 (Cd81) - 0.00396 (Cd77) - 0.0691 (Cd91) - 0.0404 (Cd99) - 0.1394 (CD87)

Cd62 = 76.111 - 0.7937 (Cd70) + 0.0709 (Cd74) - 0.0978 (Cd99) + 0.3438 (year) - 0.00471 (Cd78) + 15.389 (Cd94) + 0.0623 (Cd66) - 0.4241 (Cd88)

Cd63 = 53.575 + 0.0951 (Cd95) - 0.5671 (Cd71) + 0.0793 (Cd75) - 0.00698 (Cd79) - 0.0278 (Cd83) + 17.387 (Cd92) + 0.1651 (year) - 0.1608 (Cd87)

Cd64 = 59.008 + 0.0627 (Cd76) - 0.5712 (Cd72) + 15.981 (Cd94) - 0.1852 (Cd98) - 0.00436 (Cd80) + 0.1966 (year) - 0.1852 (Cd93) - 0.2499 (Cd88)

Cd65 = -167.356 + 1.923 (Cd69) + 0.2537 (Cd97) + 0.1818 (Cd99) - 0.607 (year) + 0.00876 (Cd77) + 0.4241 (Cd61) + 0.1715 (Cd91) - 11.579 (Cd92)

Cd66 = -88.893 + 0.2216 (Cd99) + 1.0288 (Cd70) + 0.0149 (Cd78) + 0.0943 (Cd93) + 0.4144 (Cd62) + 0.0497 (Cd82) - 0.5509 (Cd98) - 0.2951 (year)

Cd67 = -130.913 + 1.668 (Cd71) + 0.209 (Cd97) + 0.00766 (Cd79) - 0.3814 (year) - 18.131 (Cd92) + 0.2526 (Cd63) - 0.0211 (Cd83)

Cd68 = -130.597 + 1.519 (Cd72) + 0.00908 (Cd80) + 0.0939 (Cd93) + 0.0262 (Cd84) + 0.2456 (Cd64) - 0.1004 (year) - 4.403 (Cd94)

Cd69 = 93.213 + 0.1122 (Cd65) - 0.2019 (Cd 61) + 0.0397 (Cd99) - 0.1859 (Cd97) - 0.0059 (Cd81) + 5.391 (Cd92) - 0.0537 (Cd95) + 0.0053 (Cd73)

Cd70 = 100.293 - 0.2769 (Cd62) + 0.0891 (Cd66) - 0.4456 (Cd88) - 0.0177 (Cd82) - 0.0796 (Cd96) - 0.00152 (Cd78) + 0.1080 (Cd98) + 0.0157 (Cd99)

Cd71 = 88.364 + 0.1553 (Cd67) - 0.2113 (Cd63) - 0.1939 (Cd97) + 0.0298 (Cd75) + 10.957 (Cd92) + 0.0580 (year) - 0.0655 (Cd95) - 0.0475 (Cd87)

Cd72 = 91.358 + 0.1470 (Cd68) - 0.0249 (Cd64) + 0.0116 (Cd76) + 0.0224 (CD93) + 3.089 (Cd94) + 0.0386 (year) - 0.1348 (Cd88) - 0.00051 (Cd80)

Cd73 = -10.830 + 2.263 (Cd61) + 0.792 (Cd65) + 0.0153 (Cd77) - 43.779 (Cd92) - 1.212 (year) - 0.1372 (Cd81) + 0.188 (Cd99) + 0.466 (Cd69)

Cd74 = 45.019 - 7.216 (Cd88) + 1.391 (Cd62) + 0.698 (Cd66) - 0.318 (Cd82) - 1.147 (year) + 55.008 (Cd94) + 0.155 (Cd99) - 0.432 (Cd98)

Cd75 = -167.912 - 0.530 (Cd67) + 1.962 (Cd63) + 0.0188 (Cd79) - 0.693 (year) + 2.175 (Cd71) - 81.476 (Cd92) + 0.562 (Cd95) + 0.522 (Cd97)

Cd76 = -34.80 - 8.049 (Cd88) + 1.592 (Cd64) + 0.765 (Cd68) - 0.214 (Cd84) -0.592 (year) + 0.977 (Cd72) - 1.109 (Cd98) + 0.498 (Cd96)

Cd77 = -226.942 + 23.819 (year) + 30.336 (Cd97) + 5.441 (Cd65) - 3.278 (Cd99) - 10.427 (Cd61) - 1.517 (Cd81) + 9.599 (Cd95) + 2.997 (Cd91)

Cd78 = 1191.29 + 29.977 (year) + 31.328 (Cd98) + 10.280 (Cd66) - 11.902 (Cd62) - 27.991 (Cd88) - 12.852 (Cd70) + 363.78 (Cd94) - 0.932 (Cd82)

Cd79 = -93.261 + 19.804 (year) + 7.802 (Cd67) + 27.764 (Cd97) - 19.179 (Cd63) + 667.14 (Cd92) - 1..796 (Cd83) - 4.252 (Cd87) + 0.981 (Cd91)

Cd80 = 187.80 + 24.945 (year) + 28.375 (Cd98) + 8.666 (Cd68) - 15.350 (Cd64) - 21.541 (Cd88) - 1.432 (Cd84) + 136.93 (Cd94)

Cd81 = 152.91 - 3.475 (year) - 1.982 (Cd61) - 0.939 (Cd97) - 0.864 (Cd69) + 0.573 (Cd87)

Cd82 = 99.635 - 3.244 (year) + 4.088 (Cd88) + 0.457 (Cd98) - 0.463 (Cd62) - 0.792 (Cd70)

Cd83 = 48.447 - 3.148 (year) - 0.615 (Cd63) + 0.537 (Cd87)

Cd84 = 31.974 - 2.974 (year) + 2.846 (Cd88) - 0.432 (Cd64)

Cd89 = 0.0258 + 0.00868 (Cd56) - 0.00028 (Cd54) - 0.00220 (Cd88) + 0.00060 (Cd55) + 0.0240 (Cd94) - 0.00030 (Cd61) + 0.00001 (Cd77) - 0.00036 (year)

Cd90 = -5.359 + 0.196 (year) + 0.0622 (Cd66) + 0.177 (Cd53) + 0.659 (Cd56) + 0.0751 (Cd61) + 0.0260 (Cd99) + 3.027 (Cd94) + 0.0094 (Cd82)

Cd97 = 36.142 - 0.00455 (Cd77) - 0.347 (Cd69) - 0.148 (year) + 0.0279 (Cd99) + 0.0192 (Cd65) - 0.00599 (Cd81)

Cd98 = 2.324 + 0.00627 (Cd78) - 0.0823 (Cd66) + 0.0153 (Cd82) + 0.392 (Cd88) - 0.119 (year) + 0.0159 (Cd99)